Wavelength tunable laser for DANCE

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Contents

- DANCE
- Simultaneous resonance between s- and p-pol.
- The measurement of reflection phase difference between s- and p-pol.
- Future plans
- Summary

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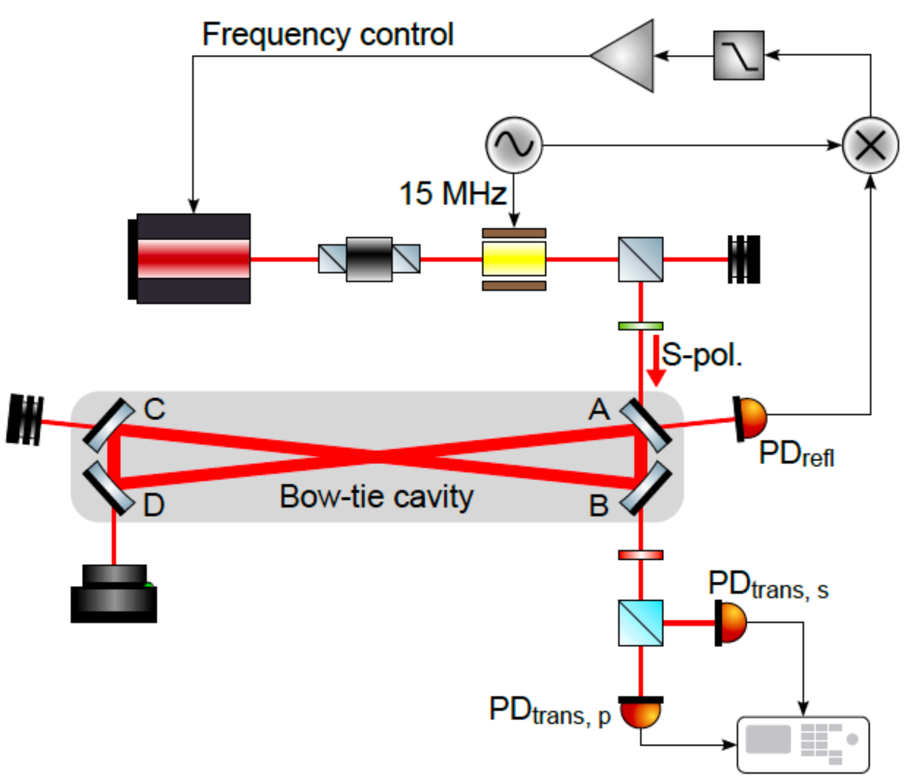
DANCE

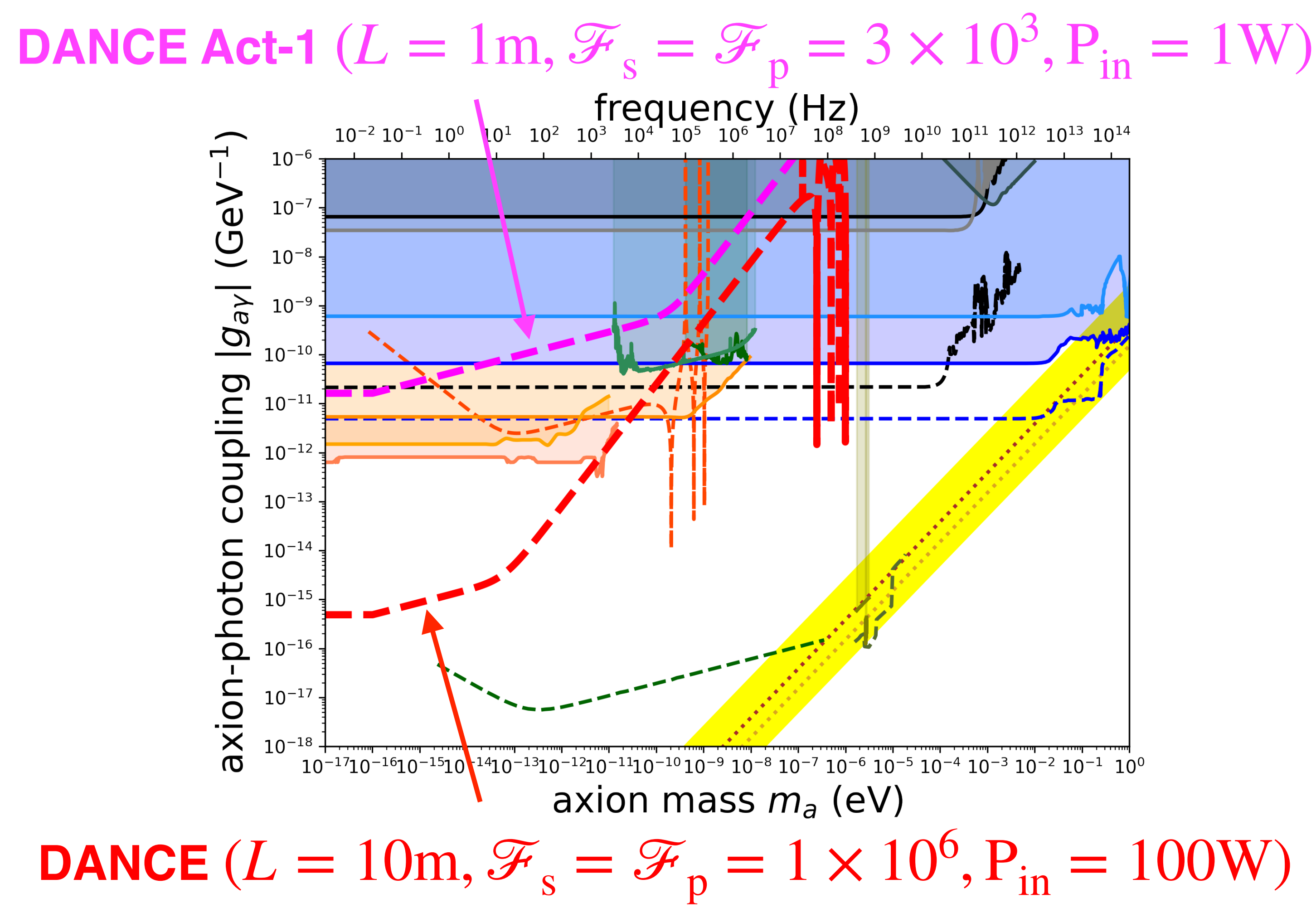
DANCE (Dark matter Axion search with riNg Cavity Experiment)

- Bow-tie ring cavity
- Dark matter search experiment by interferometer
- Prototype experiment (DANCE Act-1) is ongoing

Underway for demonstrating the proof of its principle



[1]Y. Oshima *et al.* : arXiv:2303.03594



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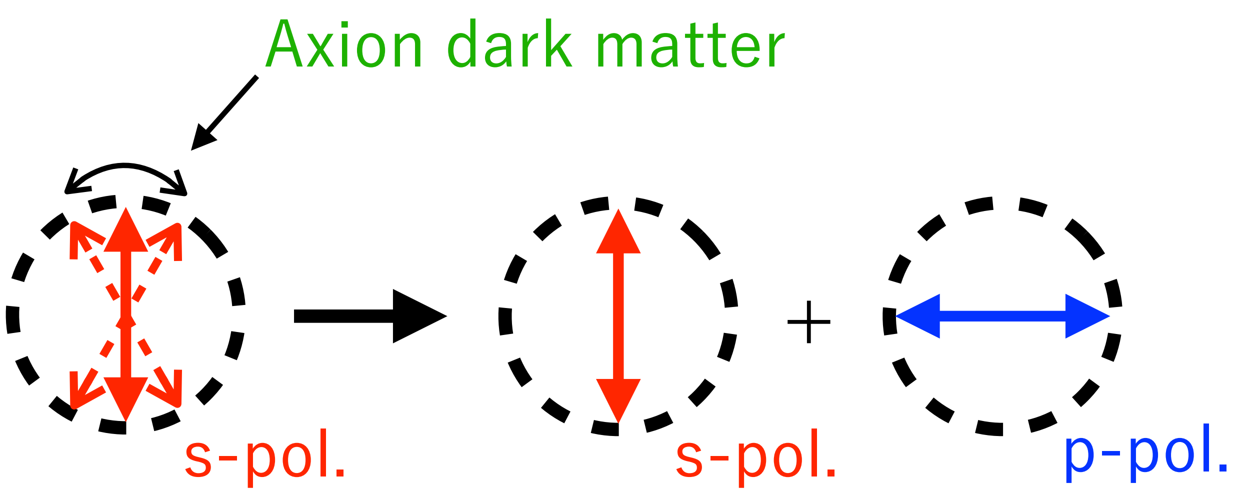
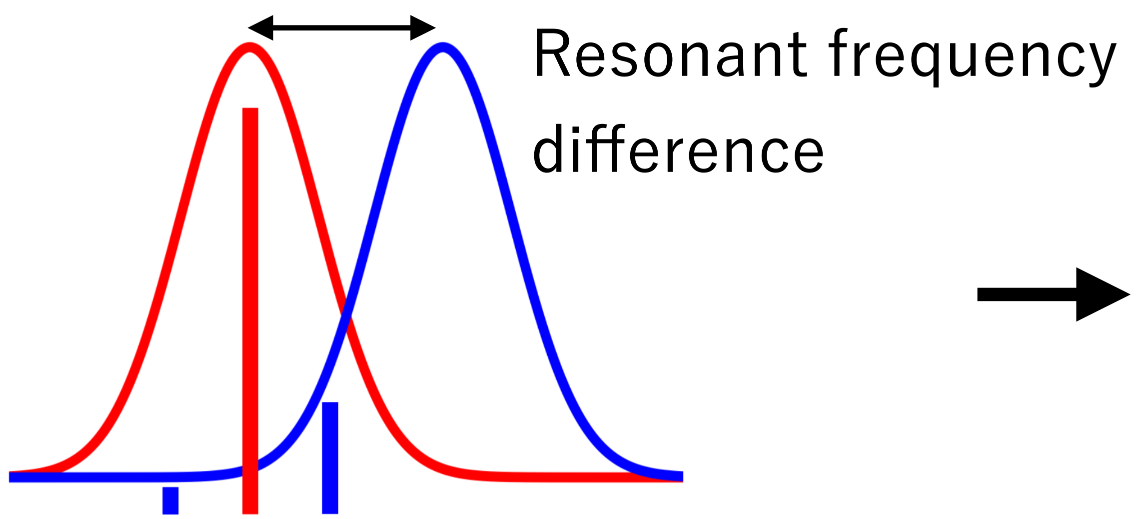
Simultaneous resonance between s- and p-pol.

Need for simultaneous resonance

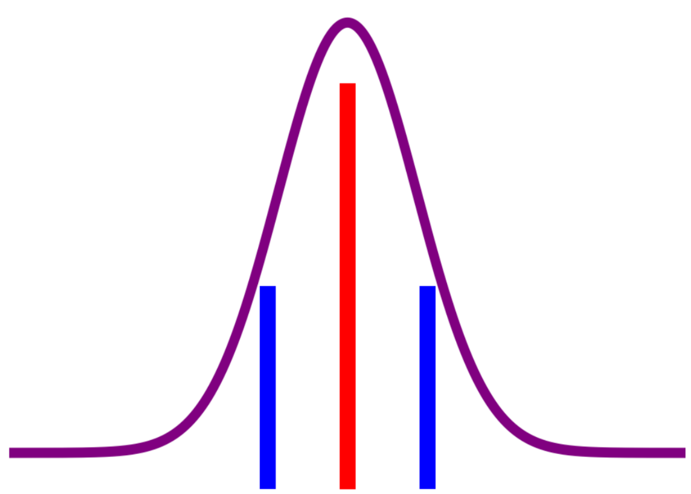
- p-pol. is produced from s-pol. by axion dark matter
  → Simultaneous resonance is necessary for increasing and detecting p-pol.



- If s-pol. and p-pol. are not simultaneous resonance, Axion signal(p-pol.) doesn't increase in the cavity. This fact degrades the sensitivity.



Difference between s-pol. and p-pol.
→Degrade sensitivity



Realize simultaneous resonance between s-pol. and p-pol.
→Improve sensitivity

Issue of simultaneous resonance

Issue of simultaneous resonance

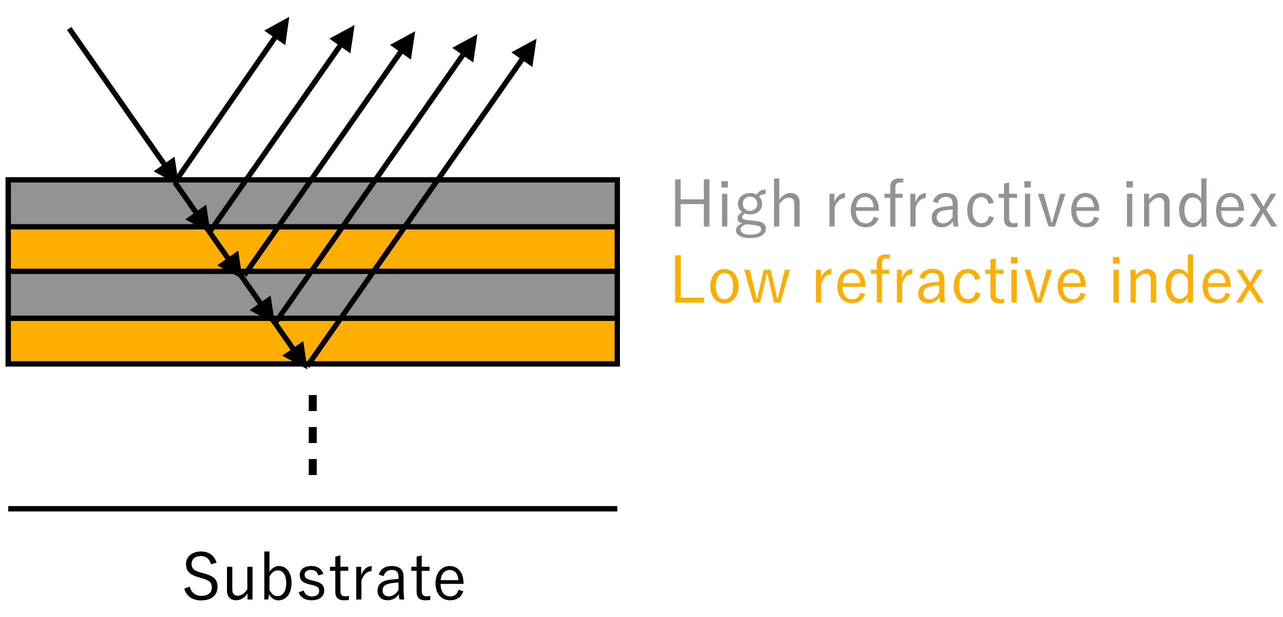
Difficult to adjust the reflection phase difference between s- and p-pol.

The cause

- Reflection phase difference occurs in oblique incidence
  - The error about thickness of dielectric multilayer mirror
  - The difference of the reflectance between s- and p-pol. on boundary of dielectric multilayer mirror

→ The cause is not cleared

Dielectric multilayer mirror

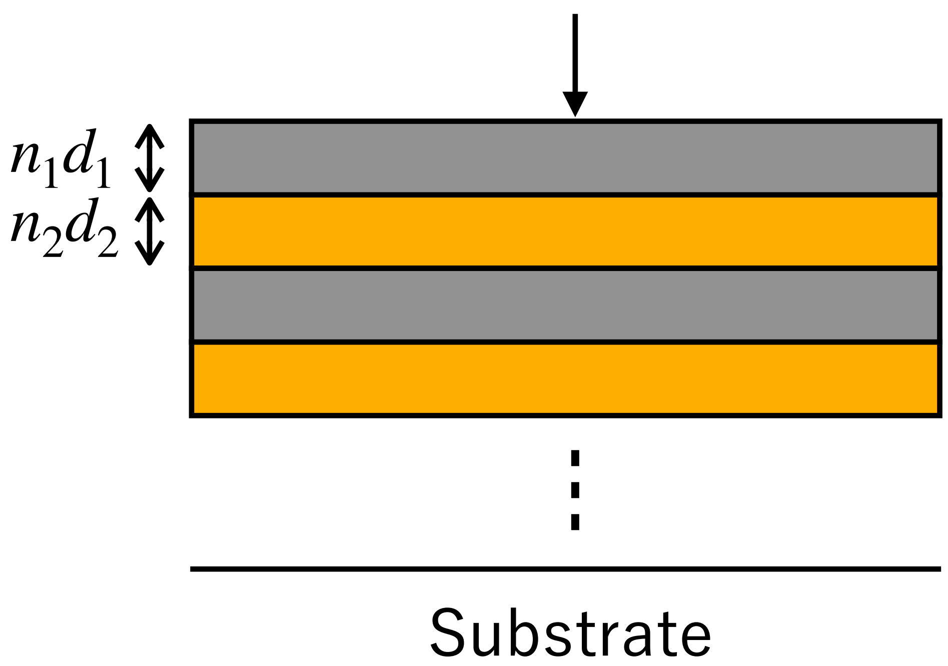


Issue of simultaneous resonance

The reflectance of a Thin Film

- Assume that the film is thin and the substrate is thick
- Electric and magnetic component parallel to the boundary, continuous across it

Normal reflection on multilayers



High index layers → no phase shift

Low index layers → change of 180[deg]

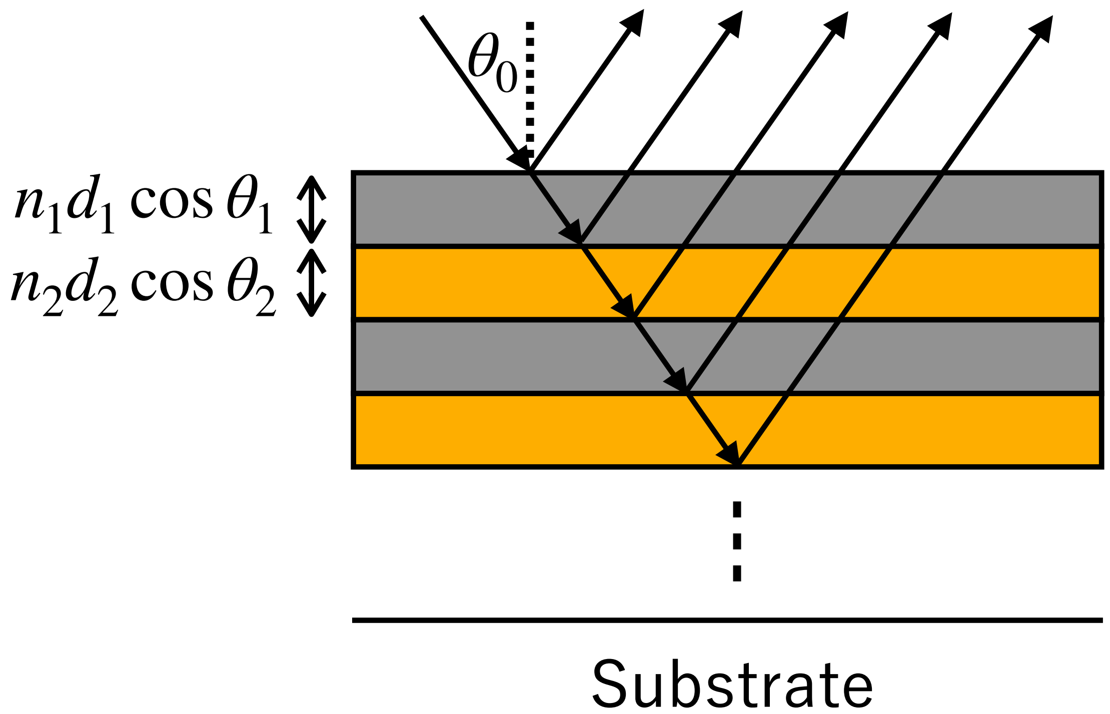
Incident angle: $\theta_0 = 0$

Optical thickness: $n_1 d_1 = n_2 d_2 = \lambda/4$

→ Higher reflectivity than a single layer

Issue of simultaneous resonance

Oblique reflection on multilayers



Incident angle: $\theta_0 \neq 0$

Optical thickness: $n_1 d_1 \cos\theta_1 = n_2 d_2 \cos\theta_2 \neq \lambda/4$

Characteristic matrix of layer m

$$M_\mathrm{m} = \begin{pmatrix} \cos\delta_\mathrm{m} & (i\sin\delta_\mathrm{m})/\eta_\mathrm{m} \\ i\eta_\mathrm{m}\sin\delta_\mathrm{m} & \cos\delta_\mathrm{m} \end{pmatrix}$$

$$\delta_\mathrm{m} = \frac{2\pi}{\lambda} n_\mathrm{m} d_\mathrm{m} \cos\theta_\mathrm{m}$$

s-pol.: $\eta_{\mathrm{m,s}} = n_\mathrm{m}\cos\theta_\mathrm{m}$

p-pol.: $\eta_{\mathrm{m,p}} = n_\mathrm{m} / \cos\theta_\mathrm{m}$

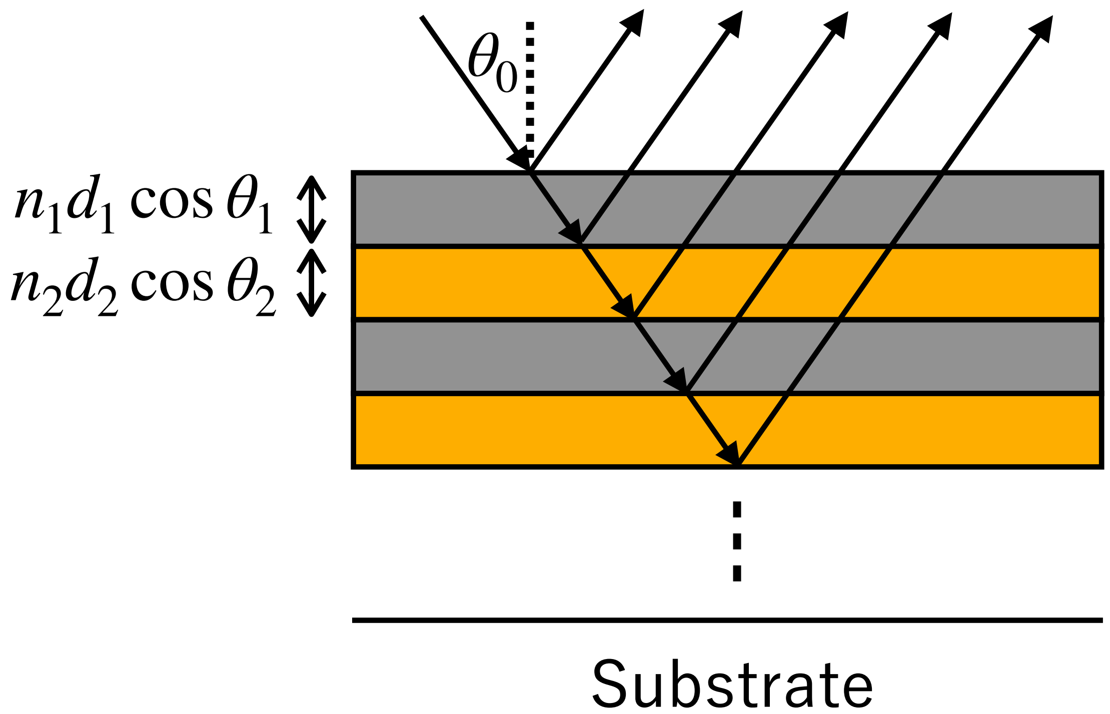
※ If $\theta_m = 0$, same as normal reflection on multilayers

→ Different for s- and p-pol. on reflectivity of a boundary due to the difference of a tilted optical admittance η_m between s- and p-pol.

→ Reflection phase difference between s- and p-pol.
Realizing $n_1 d_1 \cos\theta_1 = n_2 d_2 \cos\theta_2 = \lambda/4$ is difficult due to the accuracy for thickness of thin film

Issue of simultaneous resonance

Calculation of reflectivity



Characteristic matrix of layer m

$$M_m = \begin{pmatrix} \cos\delta_m & (i\sin\delta_m)/\eta_m \\ i\eta_m \sin\delta_m & \cos\delta_m \end{pmatrix}$$

$$\delta_m = \frac{2\pi}{\lambda} n_m d_m \cos\theta_m$$

s-pol.: $\eta_{m,s} = n_m \cos\theta_m$

p-pol.: $\eta_{m,p} = n_m / \cos\theta_m$

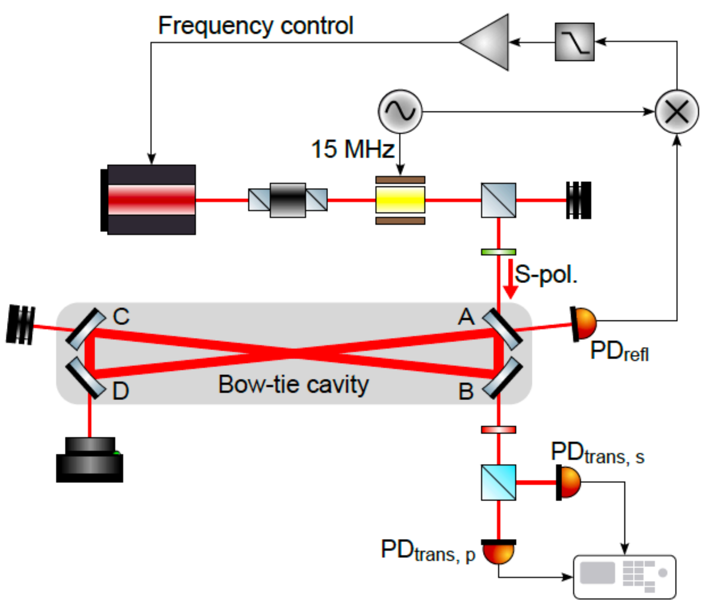
$$\begin{pmatrix} E_1 \\ H_1 \end{pmatrix} = \left[\prod_m M_m\right] \begin{pmatrix} E_n \\ H_n \end{pmatrix} \rightarrow \begin{pmatrix} E_1/E_n \\ H_1/E_n \end{pmatrix} = \begin{pmatrix} B \\ C \end{pmatrix} = \left[\prod_m M_m\right] \begin{pmatrix} 1 \\ \eta_n \end{pmatrix} \quad \eta_n = H_n/E_n$$

Reflectivity of dielectric multilayers

$$r = \frac{\eta_0 - C/B}{\eta_0 + C/B}$$

Realization of simultaneous resonance

DANCE Act-1



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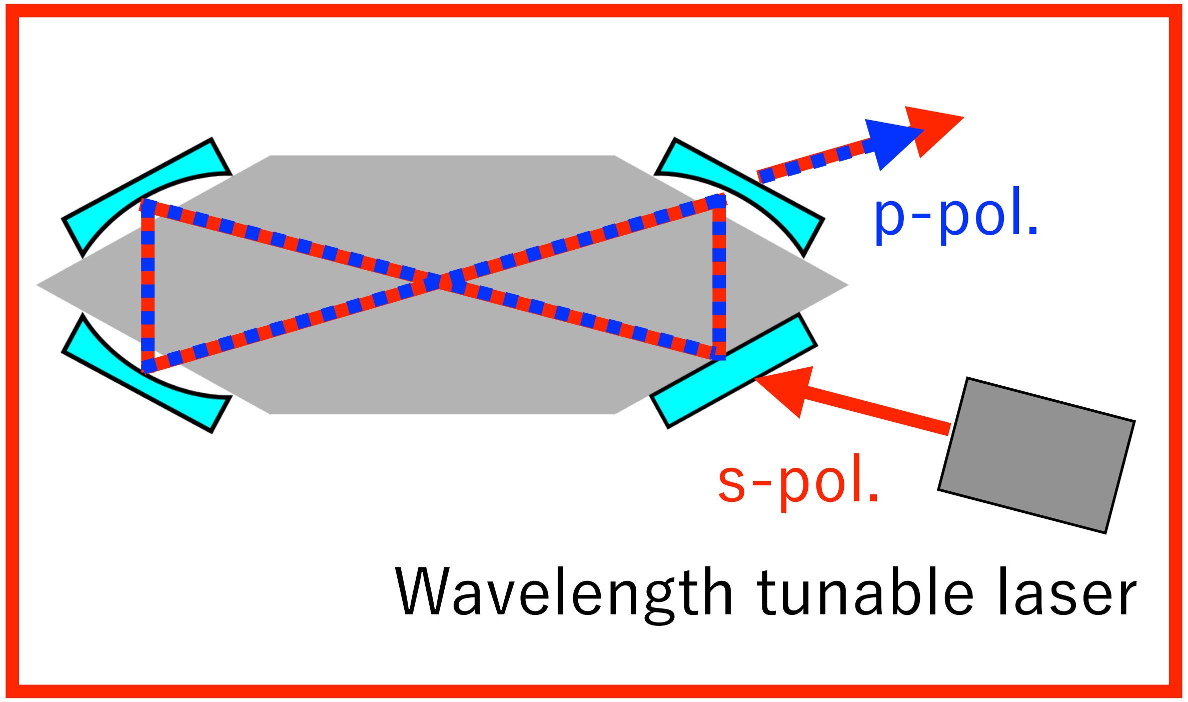
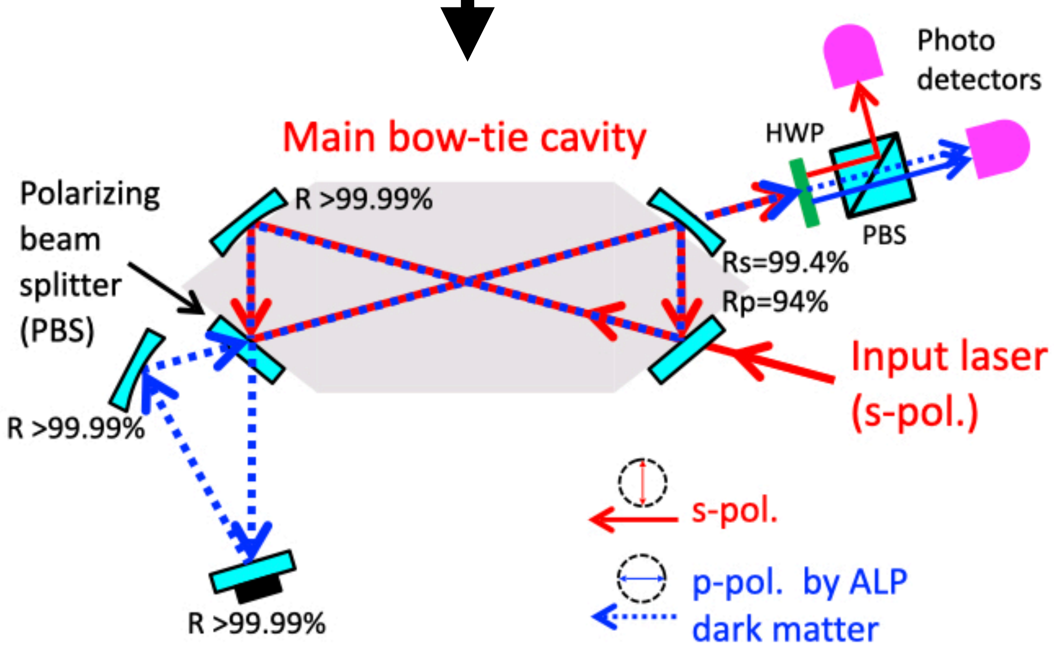




Auxiliary cavity

● The method of auxiliary cavity

→Realize simultaneous resonance by controlling s- and p-pol. independently

● The method of wavelength tunable laser

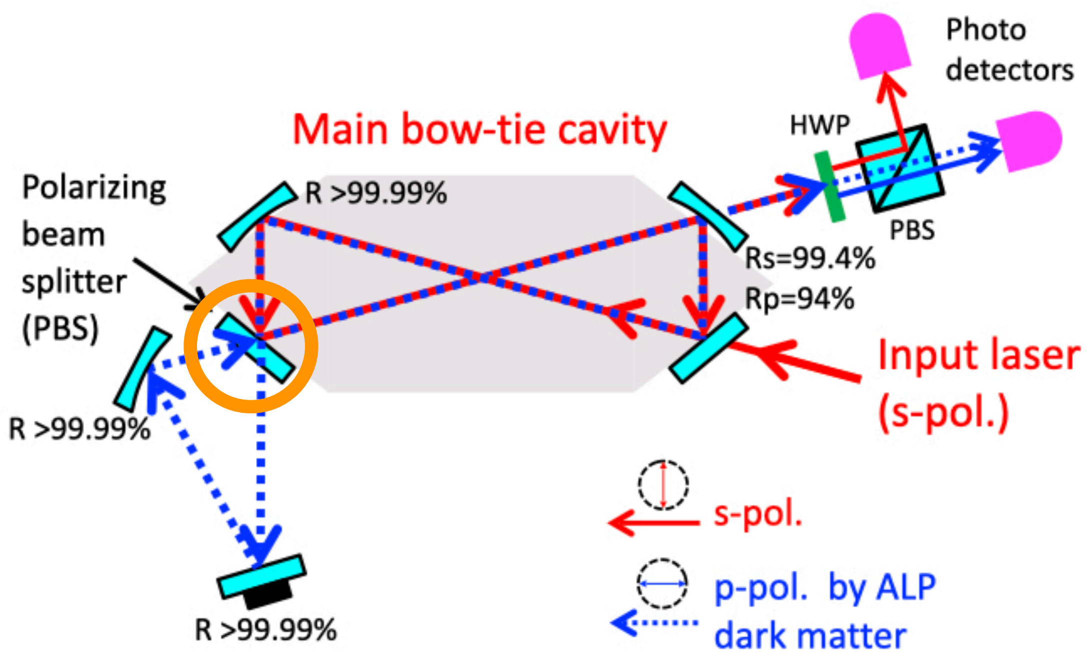
- Wavelength tunable laser

Search wavelength to cancel reflection phase difference between s- and p-pol. by sweeping wavelength

- Wavelength sensitive phase-shifting mirror

Realization of simultaneous resonance

The method of auxiliary cavity



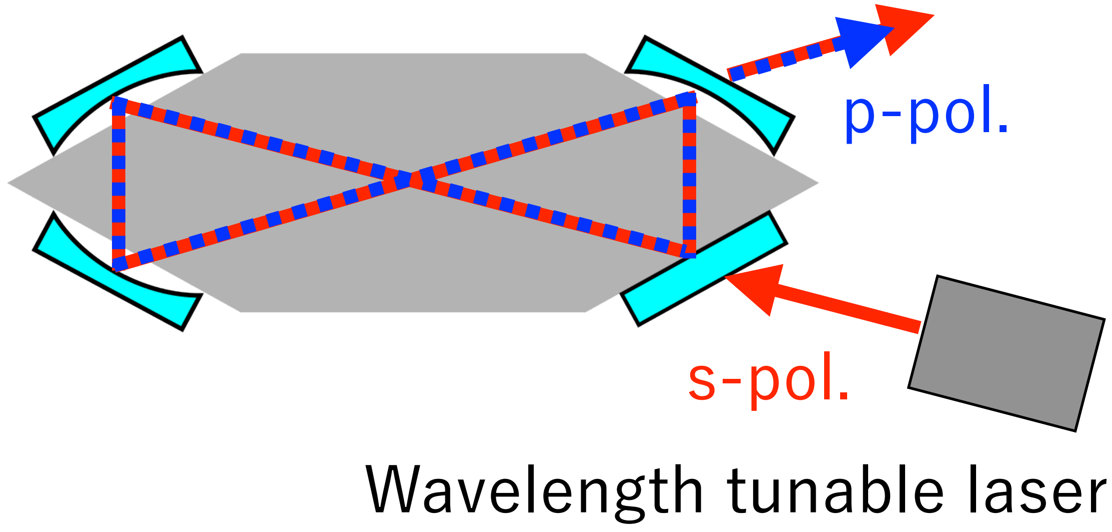
<u>Advantage</u>

Control the reflection phase difference between s- and p-pol. easily

<u>Disadvantage</u>

The loss on the AR coatings of the PBS

The method of wavelength tunable laser



<u>Advantage</u>

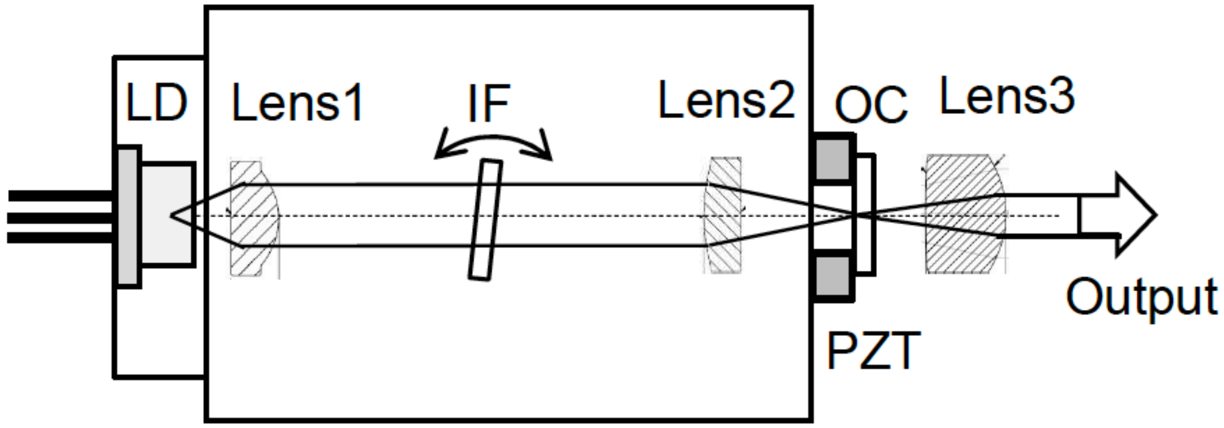
Solve the disadvantage of the method of auxiliary cavity

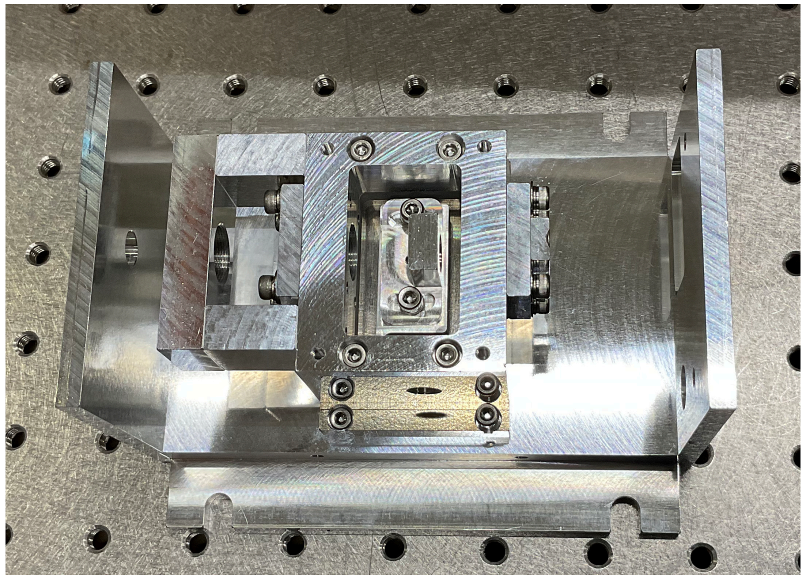
<u>Disadvantage</u>

・Difficult to conduct mirror coating to cancel the phase difference between s- and p-pol.

・Need to use stable wavelength tunable laser

Wavelength tunable laser (Nakagawa laser)





Current status

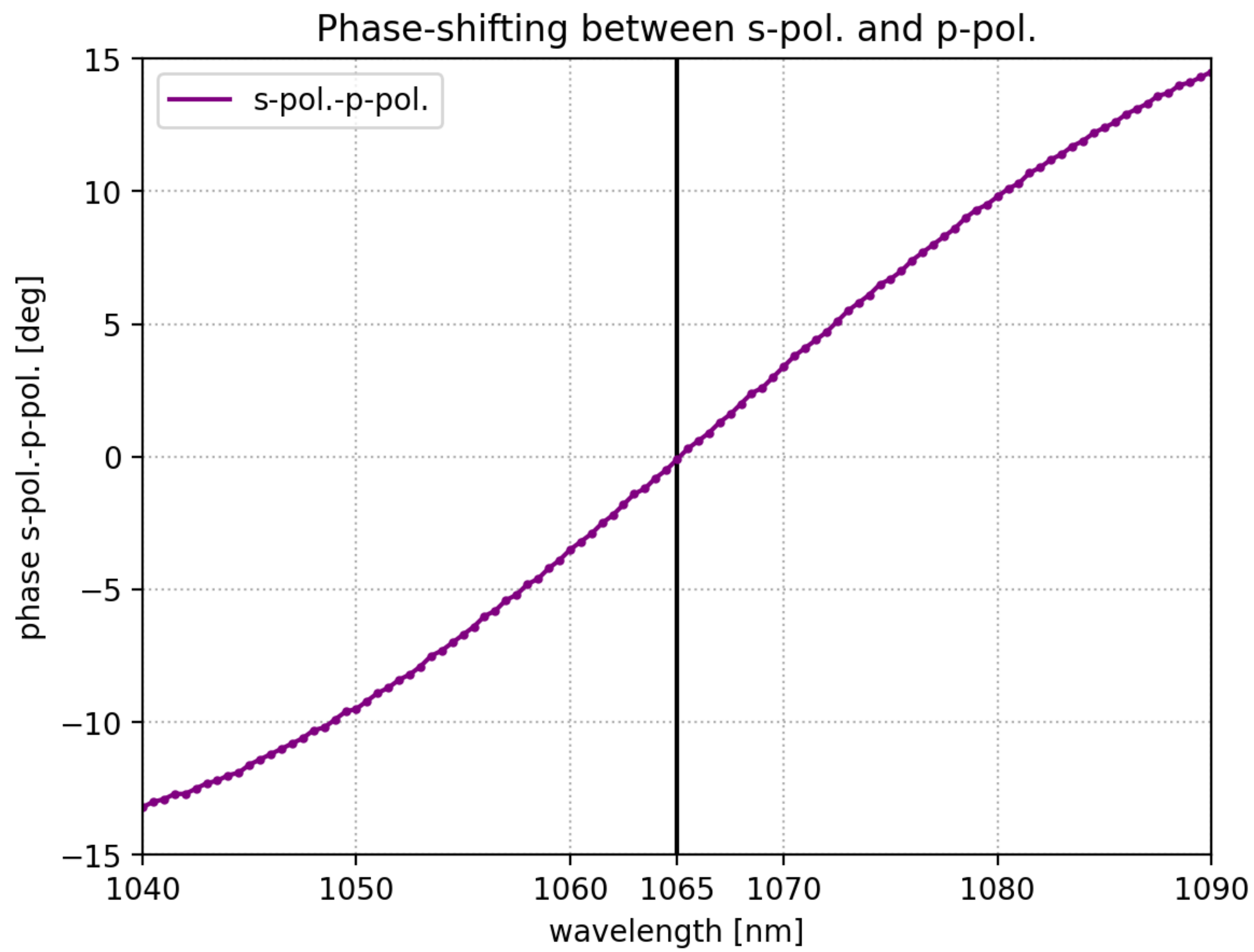
External cavity semiconductor laser

- Wavelength range：1065 ± 5nm
- Full width at half maximum： < 200kHz
- Output：20~50mW

<u>Feature</u>

- Choose wavelength by adjusting interferometer filter (IF) angle
- Closed structure external cavity→Strong against acoustic noise and vibration

Wavelength sensitive phase-shifting mirror

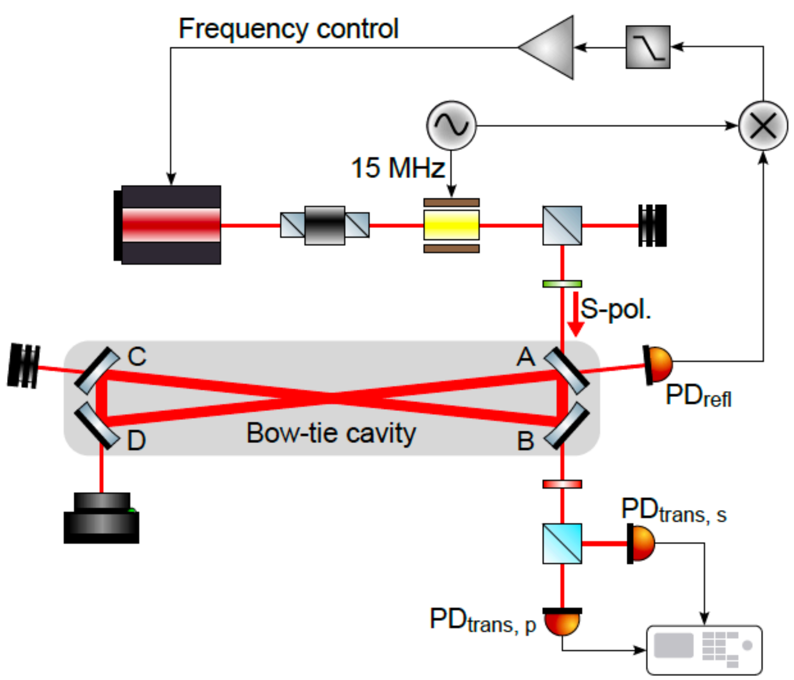


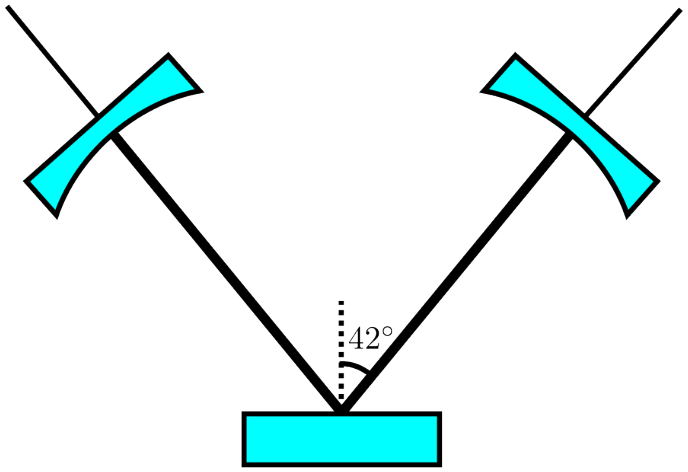
Reflection phase difference between s- and p-pol.(Layertec Inc.)

Reflection phase difference between s- and p-pol. is zero near 1065nm

→ Adjusting 1065nm on the wavelength tunable laser, conduct phase difference control to retain simultaneous resonance

Motivation





V shaped cavity

[1]Y. Oshima *et al.* : arXiv:2303.03594

<u>Issue about reflection phase difference between s- and p-pol. on DANCE Act-1</u>

- DANCE Act-1 consists of 4 mirrors. Then, we calculate reflection phase difference between s- and p-pol. per mirror and determine sensitivity[1]

→Measure reflection phase difference between s- and p-pol. per mirror to minimize the error

- There is the possibility that reflection phase difference between s- and p-pol. per mirror is drifting

→Investigate the amount of control by obtaining the time-series data about reflection phase difference between s- and p-pol.

⟶ Considered experimental setup (V shaped cavity)

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V shaped cavity

<u>Design value</u>

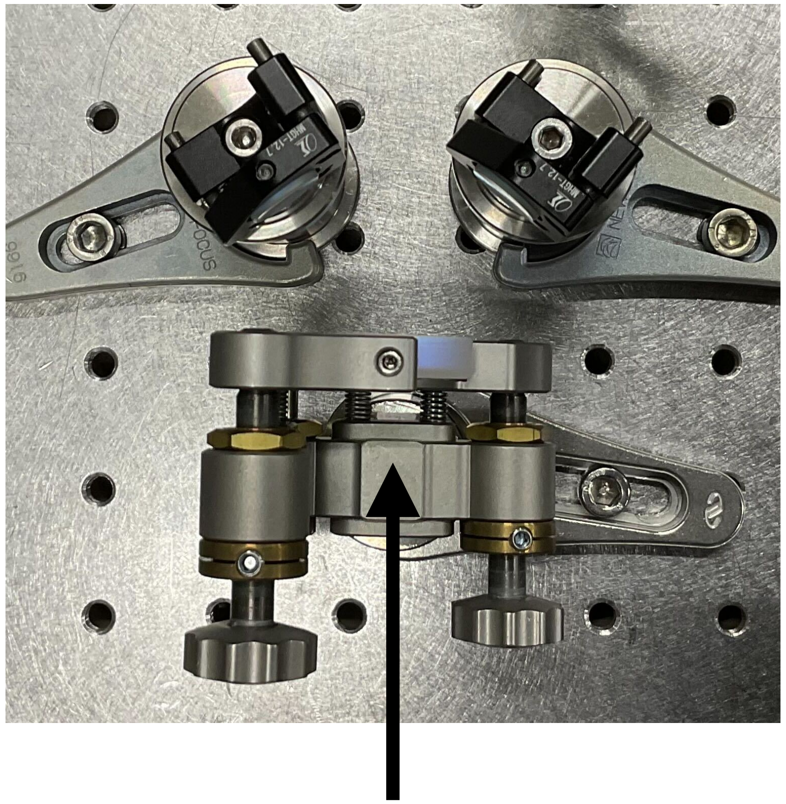
- Incident angle：42deg
- Cavity length L：60mm
- Center of curvature R_i：

  Front and end mirror: 50mm

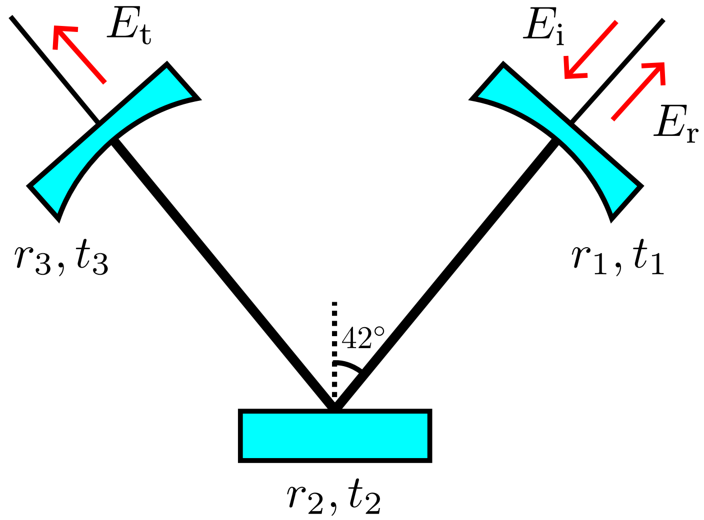
  Test mirror: flat
- Reflectance r_i：

  Front and end mirror: 99 %

  Test mirror: 99.9 %



Test mirror



<u>Purpose</u>

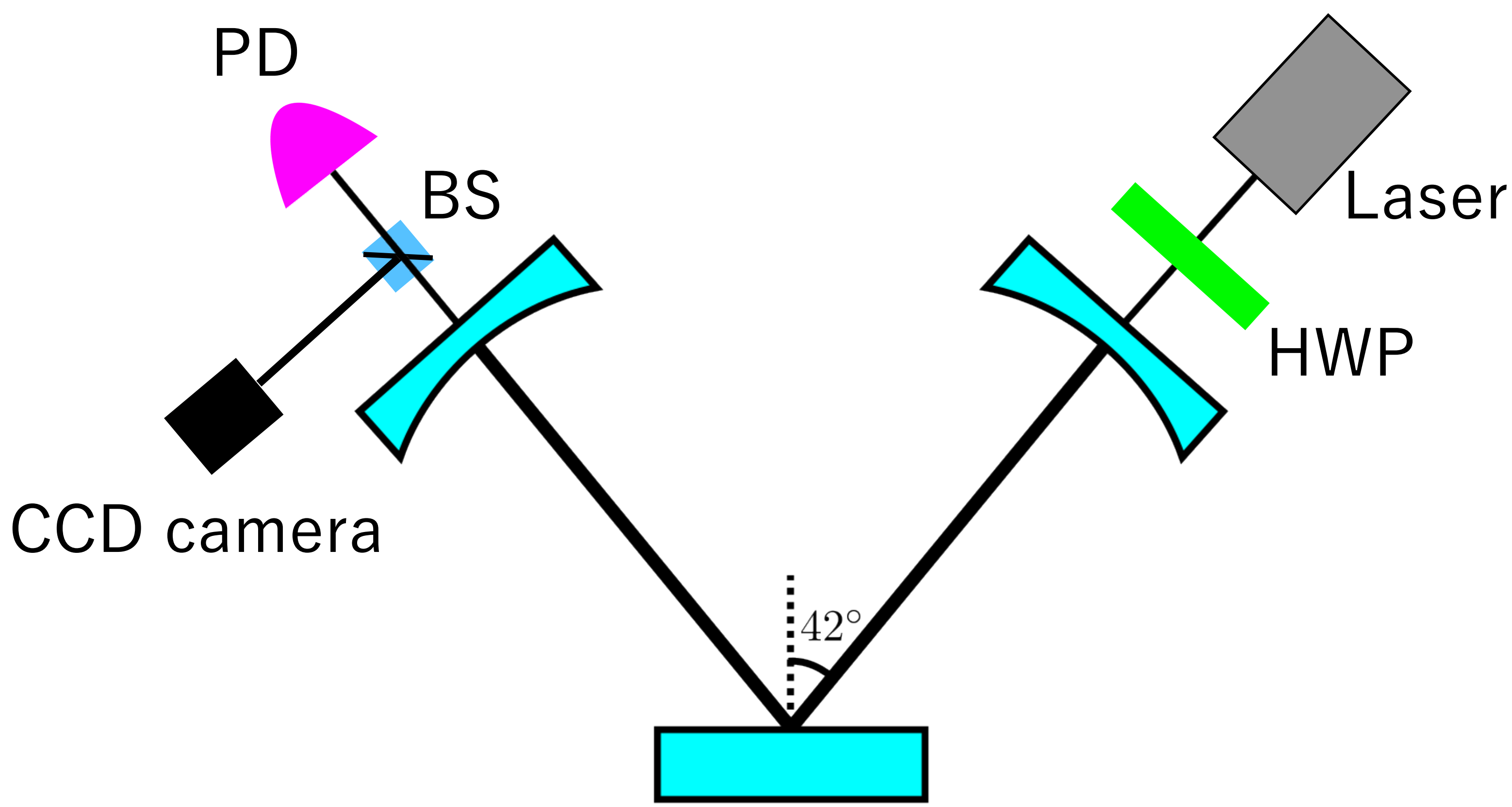
- The measurement of reflection phase difference between s- and p-pol.
- Investigation about drifting of reflection phase difference between s- and p-pol.

  →Going to obtain the time-series data about phase difference drift

Reflection phase difference between s- and p-pol.

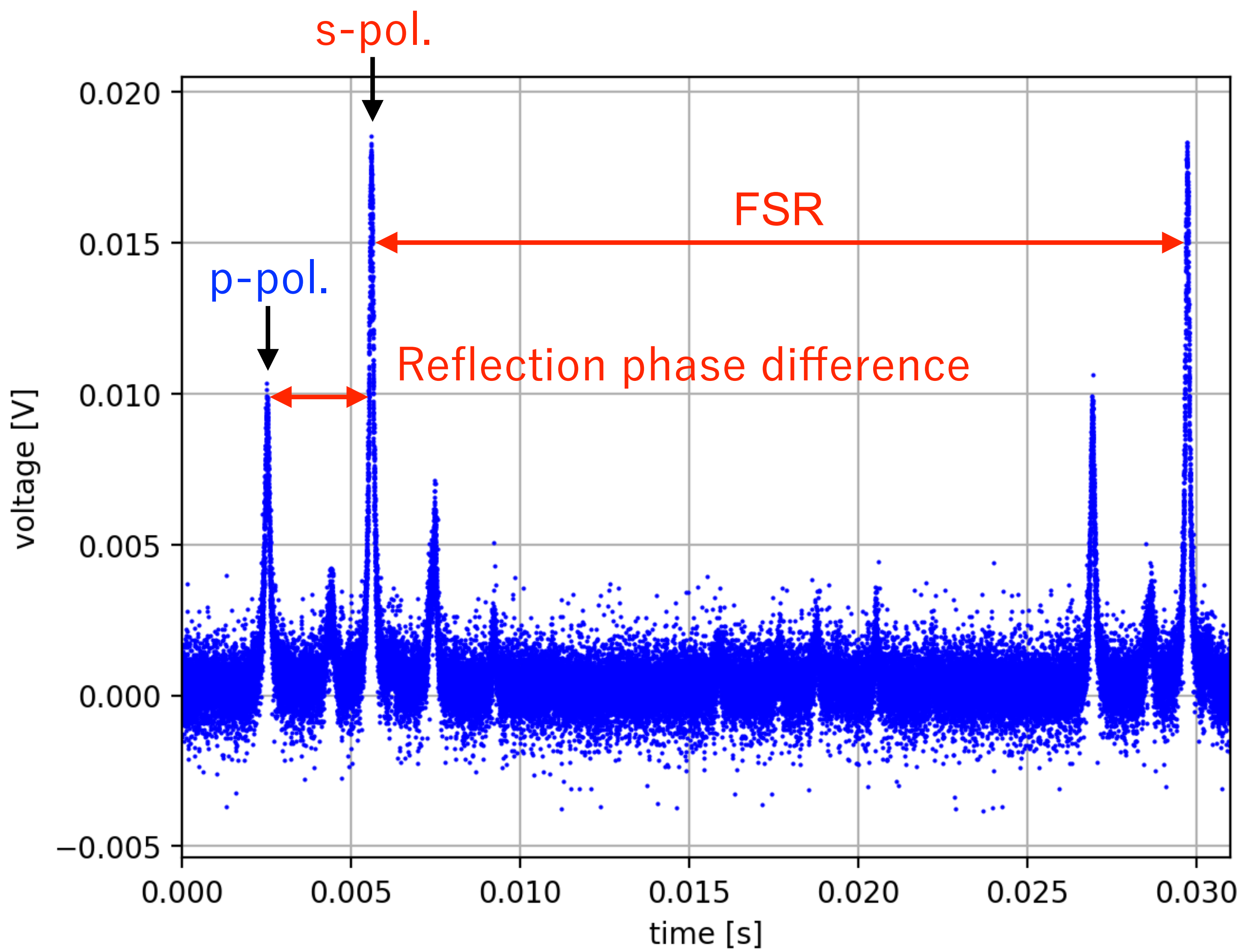
Purpose

The measurement of reflection phase difference between s- and p-pol. per mirror



Injected the s- and p-pol. into the cavity, observing transmitted light

Measurement result of reflection phase difference between s- and p-pol.



Measurement result by my experiment $\Delta\phi = 23.3 \pm 0.5$[deg]

Measurement result by DANCE Act-1 $\Delta\phi = 21.6 \pm 1.2$[deg]

→ Suppress the error

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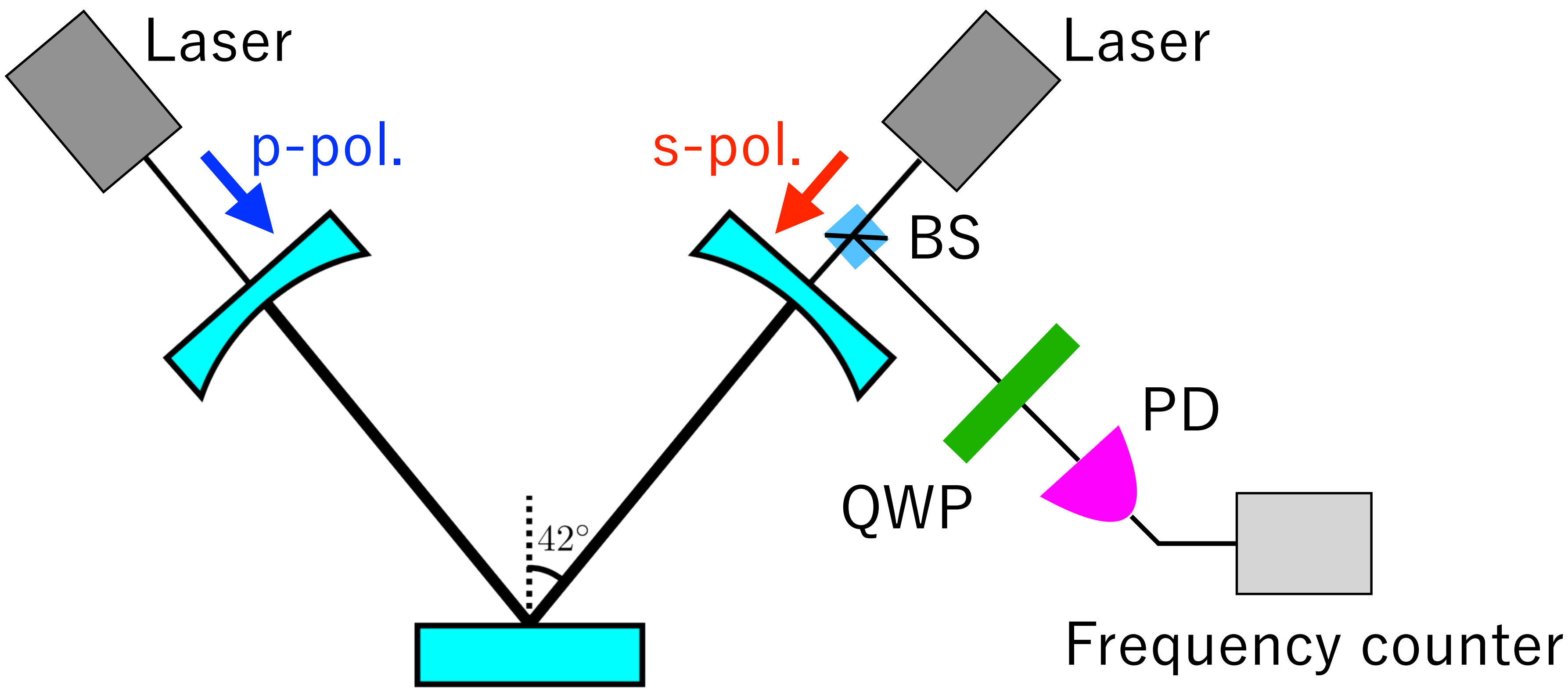
Time-series data about reflection phase difference between s- and p-pol.

Purpose

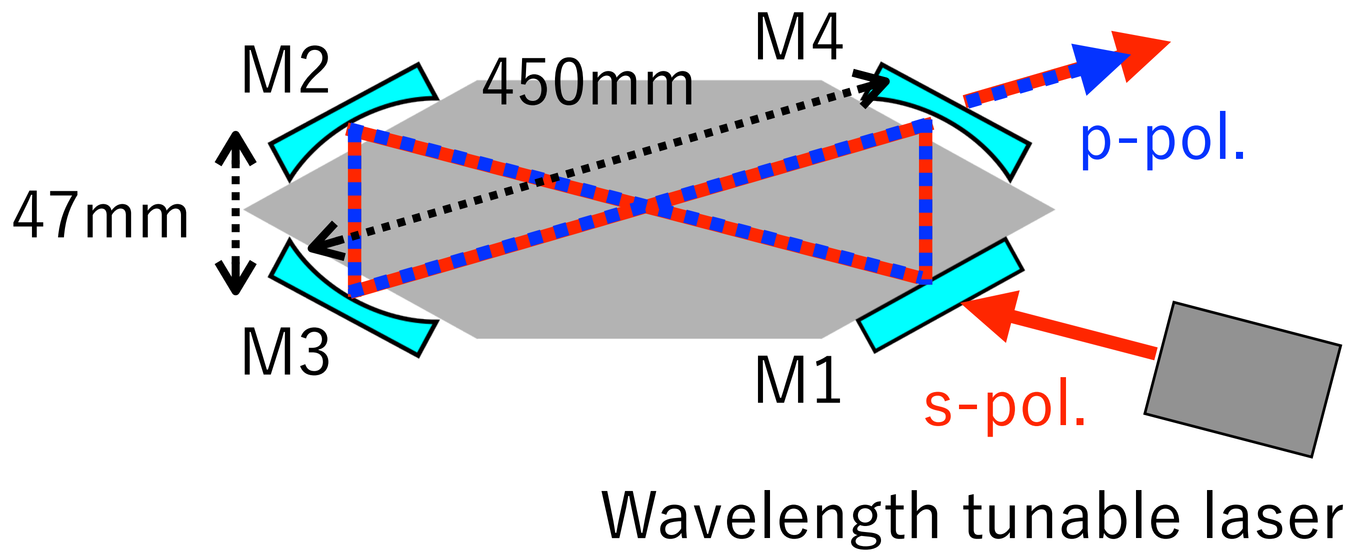
Investigation about the amount of control reflection phase difference between s- and p-pol.



① Inject s- and p-pol. into a cavity by using 2 laser sources

② Conduct frequency control independently, obtain time-series data about reflection phase difference between s- and p-pol.

The method of wavelength tunable laser



DANCE @B207

Mirror	Reflectivity	Curvature
M1	99.9%	Flat
M2	>99.9%	1000mm
M3	>99.9%	1000mm
M4	>99.9%	1000mm

FSR: $\nu_{FSR} = 150.9\text{MHz}$

FWHM: $\nu_{FWHM} = 96.1\text{kHz}$

Finesse: $\mathscr{F} = 1570$

Conduct phase difference control to retain simultaneous resonance

Schedule (2023)

May	June	July	August
Obtain the time-series data Prepare spacer for V shaped cavity	Evaluate wavelength sensitive phase-shifting mirror	Realize simultaneous resonance by using wavelength tunable laser	

September	October	November	December
	Evaluate the cavity Data analysis (rotation spectrum, estimate sensitivity) Write master thesis		

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Summary

- Simultaneous resonance is needed for detection of axion dark matter
  →Suggested the method of wavelength tunable laser
- The measurement of reflection phase difference between s- and p-pol.

Future plans

- Investigate the amount of control by obtaining the time-series data about reflection phase difference between s- and p-pol.
- Aim to realize simultaneous resonance by using wavelength tunable laser